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REVIEW ARTICLE

Global perspective of municipal solid waste and landfill leachate: generation, composition, eco-toxicity, and sustainable management strategies

Ali Mohd Yatoo[1,2] · Basharat Hamid[2] · Tahir Ahmad Sheikh[3] · Shafat Ali[1] · Sartaj Ahmad Bhat[4,5] · Sudipta Ramola[6] · Md. Niamat Ali[1] · Zahoor Ahmad Baba[3] · Sunil Kumar[5]

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Abstract

Globally, more than 2 billion tonnes of municipal solid waste (MSW) are generated each year, with that amount anticipated to reach around 3.5 billion tonnes by 2050. On a worldwide scale, food and green waste contribute the major proportion of MSW, which accounts for 44% of global waste, followed by recycling waste (38%), which includes plastic, glass, cardboard, and paper, and 18% of other materials. Population growth, urbanization, and industrial expansion are the principal drivers of the ever-increasing production of MSW across the world. Among the different practices employed for the management of waste, landfill disposal has been the most popular and easiest method across the world. Waste management practices differ significantly depending on the income level. In high-income nations, only 2% of waste is dumped, whereas in low-income nations, approximately 93% of waste is burned or dumped. However, the unscientific disposal of waste in landfills causes the generation of gases, heat, and leachate and results in a variety of ecotoxicological problems, including global warming, water pollution, fire hazards, and health effects that are hazardous to both the environment and public health. Therefore, sustainable management of MSW and landfill leachate is critical, necessitating the use of more advanced techniques to lessen waste production and maximize recycling to assure environmental sustainability. The present review provides an updated overview of the global perspective of municipal waste generation, composition, landfill heat and leachate formation, and ecotoxicological effects, and also discusses integrated-waste management approaches for the sustainable management of municipal waste and landfill leachate.

Keywords Global waste · Landfill heat · Recycling · Fire hazards · Health effects · Global warming · Integrated waste management

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✉ Ali Mohd Yatoo
aliyatoo123@gmail.com

[1] Centre of Research for Development, University of Kashmir, Srinagar 190006, Jammu and Kashmir, India

[2] Department of Environmental Sciences, University of Kashmir, Srinagar 190006, Jammu and Kashmir, India

[3] Faculty of Agriculture, SKUAST-Kashmir, Jammu and Kashmir, Wadura 193201, India

[4] River Basin Research Centre, Gifu University, 1-1 Yanagido, Gifu, Japan

[5] Waste Re-Processing Division, CSIR-National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur 440020, India

[6] Zhejiang University of Technology, Hangzhou 310014, China

Abbreviations

MSW	Municipal solid waste
HMs	Heavy metals
LFG	Landfill gas
ETs	Elevated temperatures
LF	Landfill
WHO	World Health Organization
BIS	Bureau of Indian Standards
MW	Municipal waste
PM	Particulate matter
GHGs	Greenhouse gases
VOCs	Volatile organic compounds
BOD	Biological oxygen demand
COD	Chemical oxygen demand
MWM	Municipal waste management
SWM	Solid waste management
SW	Solid waste

Introduction

The worldwide generation of municipal solid waste (MSW) is rapidly mounting due to industrial development and rising living and economic standards (Peng et al. 2023; Khan et al. 2022). Every year, nearly 2.1 billion tonnes of MSW are produced globally, of which 33 percent is improperly managed (Lino et al. 2023). Recently, it has been reported that MSW production is likely to mount to 3.4 billion tonnes by the year 2050 (Statista 2023; Kaza et al. 2018). The top three producers of MSW are the USA, China, and India (Statista 2023; United Nations 2019). In recent years, rapid urbanization, particularly in developing nations, has also drastically amplified MSW generation (Peng et al. 2023; Harris-Lovett et al. 2018). Around 54 percent of the population of the globe is estimated to reside in cities, with that number likely to climb to 68 percent by 2050 (UN DESA 2018). MSW generation per capita has also increased dramatically as the lifestyles and social/economic status of people living in metropolitan areas have improved (Gour and Singh 2023; Sharholy et al. 2007). Augmented use of commodities and services also results in the massive production of MSW (Toro and Morales 2018). The municipal waste (MW) constituents vary depending on income, as people with low and middle income produce mostly organic trash, while people with high income generate more metals, glassware, and wastepaper (Kumar and Samadder 2017). Throughout the globe, MSW generation has a wide range of environmental consequences, including GHG emissions, plastic, and water pollution (Vinti et al. 2023; Chen et al. 2020).

Management of MSW comprises recycling, incineration, conversion to energy, landfilling, and composting (Waqas et al. 2023; Khan et al. 2022; Nandhini et al. 2022). However, because of its low cost and minimal technical requirements, landfilling is one of the most frequently employed techniques for disposing of MSW (Manjunatha et al. 2023). For example, in the USA, approximately 52.6 percent of MSW is discarded in landfills (Sun et al. 2019), 59.1 percent in Brazil (Costa et al. 2019), 85 percent in the kingdom of Saudi Arabia (Ouda et al. 2016), 94.5 percent in Malaysia (Tan et al. 2014), and 79 percent in China (Havukainen et al. 2017). However, landfilling has significant societal, health, and environmental issues (Mor and Ravindra 2023; Naddeo et al. 2018). In landfills, MSW undergoes physicochemical and biological interactions, liberating elements, gases, and nutrients (Zornoza et al. 2016; Regadío et al. 2015). The organic fraction of waste also attracts different pathogens, especially bacteria and viruses, which can cause significant or long-term diseases in living beings (Han et al. 2022; Van Fan et al. 2018). A significant amount of leachate, heat, and landfill gases such as CO_2 and CH_4 are generated during the waste decomposition process (Chavan et al. 2019). The heat generation may persist even after the dumping ground is closed (Chavan and Kumar 2018). In underdeveloped nations, the risk of landfill fires is great since most landfills are non-engineered (Chavan et al. 2019).

Landfill leachate is believed to be one of the serious ecological concerns linked to MSW (Mor and Ravindra 2023). The leachate amount and quality are both largely determined by the volume, moisture content, and components of solid waste (SW), as well as climatic and hydrogeological conditions (Kamaruddin et al. 2017; Adhikari et al. 2014). It mainly contains inorganic salts, organic compounds, heavy metals (HMs), and other contaminants (Abdel-Shafy et al. 2023; Shen et al. 2018) and has a strong potential to affect the environment and public health (Ambujan and Thalla 2023). The landfill leachate can also make its way into water resources, leading to water pollution (Samadder et al. 2017). Landfill leachate is harmful both in the short and long term and is considered dangerous as its infiltration into underground water can lead to biological magnification (Mishra et al. 2019).

Thus, in order to ensure sustainable waste management and safeguard human health, the transition from traditional waste dumping methods to advanced technology is a key requirement. These advanced thermochemical and biological techniques include incineration, pyrolysis, liquefaction, gasification, anaerobic digestion, and composting, which will not only help to reduce waste volume, generate clean energy, and produce stable organic fertilizer (Waqas et al. 2023; Singh et al. 2020; Shah et al. 2019), but will also provide numerous job opportunities to unemployed youth (Sharif et al. 2018). Furthermore, global interest in diverting MSW for recycling and the production of energy is considerably preferable to landfilling owing to fewer environmental implications, including lesser emission of greenhouse gases, decreased pollution, and high energy recovery potential. This article discusses the global perspective of MSW, landfill leachate, their related impacts, and sustainable waste management approaches that can assist MSW management authorities and researchers in developing more effective strategies.

Municipal solid waste generation and composition: a global perspective

Waste generation

MSW is a diverse range of waste often generated daily in different social sectors such as homes, agriculture, commercial units, hospitals, municipal collection, and treatment plants (Bhat et al. 2018). Households are the major MSW-generating sources, contributing 44–75% of the entire waste produced (Qonitan et al. 2021). Fereja and Chemeda (2022) recently reported that an average of 0.475 kg of garbage is produced by residential homes per inhabitant per day. However, the rate of MSW generation increases during the holidays and summer (Rafiee et al. 2018). The global production of MSW per year is more than two billion tonnes (Kaza et al. 2018), with the USA, China, India, Brazil, and Indonesia being the biggest producers of waste globally (Fig. 1) (UN 2019). Worldwide, the mean amount of waste generated person^{-1} day^{-1} is 0.74 kg (Kaza et al. 2018). However, the rate of MSW generation per capita per day is higher in developed countries compared to developing countries like Brazil, China, and India (Fig. 2) (Statista 2022).

Generally, there is a direct relationship between waste production and income level (Kumar and Agrawal 2020). Despite having only 16% of the world's population, high-income nations produce 34% of the world's waste. Low-income nations have 9% of the global population but produce only around 5% of the global waste (Kaza et al. 2018). Taking about region-wise waste generation, presently, the East Asia and Pacific region produces the majority of the world's waste (23%), Sub-Saharan Africa (9%), and the Middle East and North Africa region produces the least amount (6%). However, by 2050, global waste production is projected to hit around 3.5 billion tonnes per year (Statista 2023; Kaza et al. 2018) (Fig. 3), with Sub-Saharan Africa and South Asia producing 15% (516 million tonnes) and 19% (661 million tonnes) of global waste, respectively. While North America is anticipated to produce approximately 12% (396 million tonnes), and the Middle East and North Africa will produce the least around 8% (Kaza et al. 2018) (Fig. 4). Thus, in the next few decades, regions with a high proportion of growing low- and middle-income nations, such as South Asia and Sub-Saharan Africa, are likely to experience a greater rate of waste generation than regions like Europe and North America.

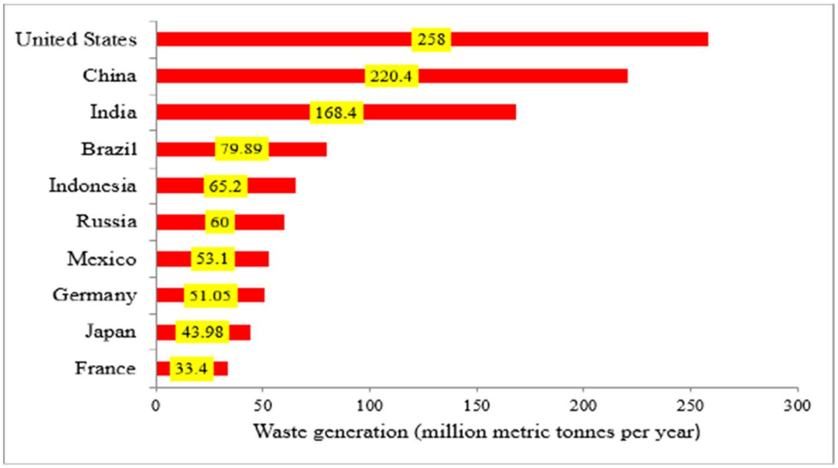


Fig. 1 Top 10 municipal solid waste (United Nations 2019)

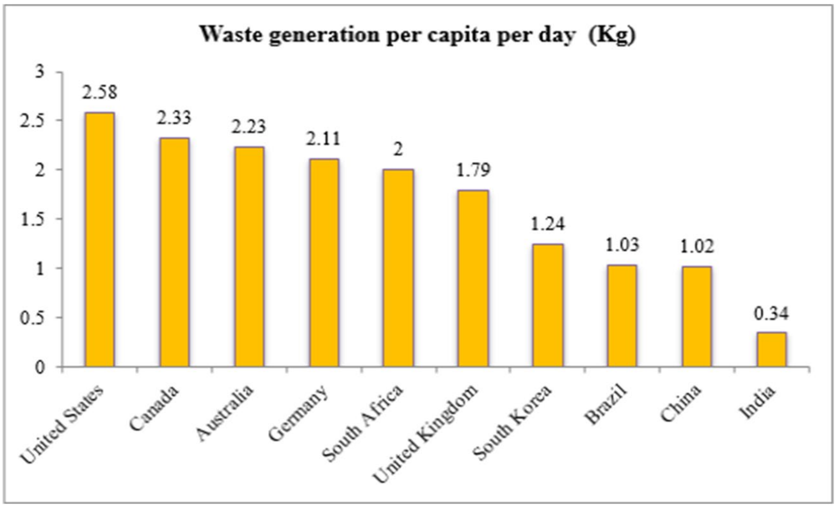


Fig. 2 Per capita generation of solid waste (Statista 2022)

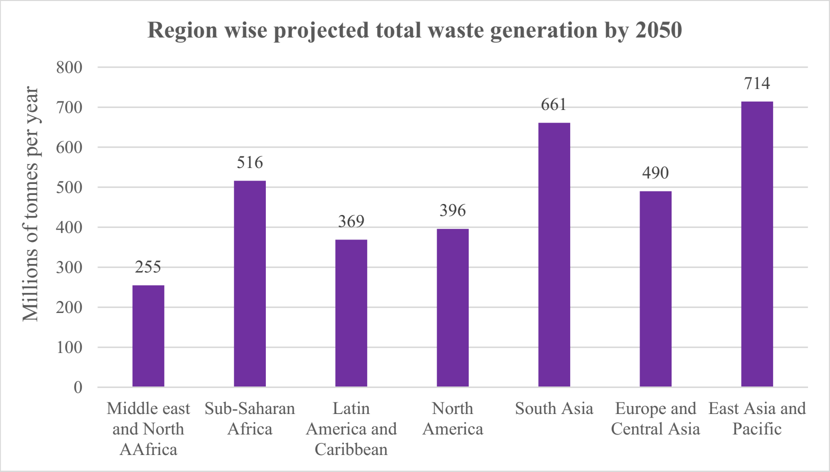


Fig. 3 By 2025, around 3.5 billion tonnes of global waste will be generated

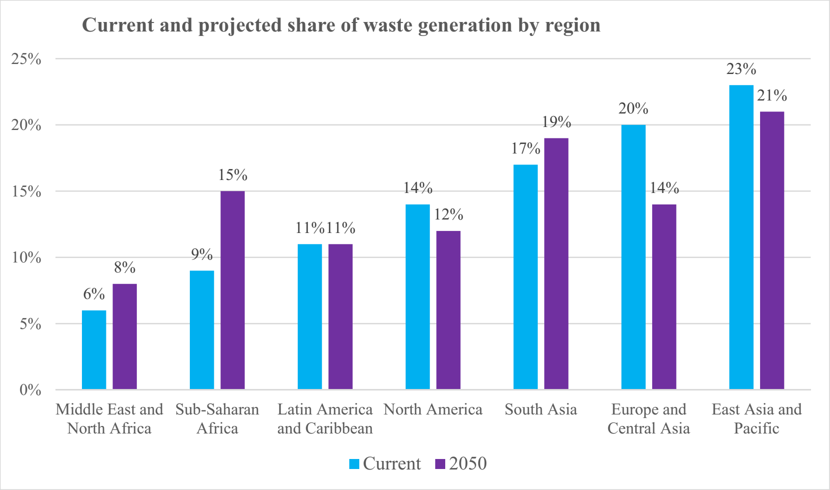


Fig. 4 Currently, East Asia and the Pacific, Europe, and North America generate the highest amount of global waste, but by 2050, the share of global waste generation in high-income countries is predicted to decrease, while in low- and middle-income countries like South Asia and Sub-Saharan Africa, the share of global waste generation is predicted to increase

Municipal solid waste composition

Waste composition is the categorization of the types of materials in MSW. MSW consists of different physical components, including paper, wood, plastic, cans, yard trimmings, glass, rubber, metal, fruit waste, batteries, paints, and pharmaceutical products (Kumar and Samadder 2023; Nandhini et al. 2022). On a global scale, food and green waste make up the majority of MSW (44% of the global waste), followed by recycling waste (38%), which includes plastic, glass, cardboard, metal, and paper, and 18% of miscellaneous materials (Fig. 5) (Zhu et al. 2021; Kaza et al. 2018). The composition of waste varies with income level, indicating different consumption habits. High-income nations produce more dry waste that can be recycled and comparatively less food and green waste, while low-income nations produce more food and green waste and less waste that could be recycled (He et al. 2022; Kumar and Samadder 2017). Across the globe, on average, all regions produce at least 50% or more organic waste, with the exception of Europe, Central Asia, and North America, which produce more dry waste (Abylkhani et al. 2021; Kumar and Agrawal 2020). The typical composition of MSW generated in different countries around the globe is presented in Table 1.

Landfill heat generation: mechanism and factors involved

The primary by-product of the landfilling of MSW is heat (Akhtar et al. 2023). Long-term high temperatures have been documented in MSW dumps across the world under various operational settings and climate locations (Yeşiller et al. 2016). The temperature elevation in MSW landfills is linked to a slew of problems, including concerns related to functioning and regulation, in addition to the destruction to landfill gas and leachate collecting facilities (Jafari et al. 2017; Luettich Scott and Yafrate 2016). During the gas collection and control activities, the atmospheric air frequently influxes into landfills, which results in the anaerobic decomposition

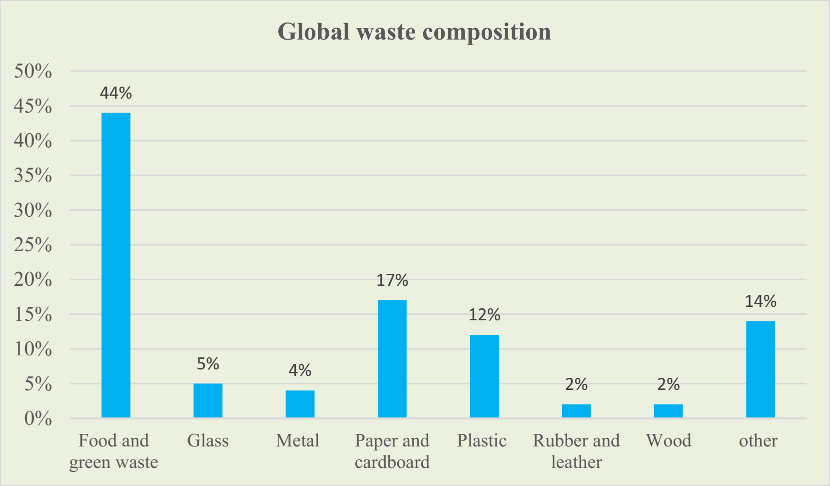


Fig. 5 Food and green waste account for the highest percentage of municipal solid waste, followed by materials that can be recycled like paper and cardboard, plastic, glass, and metal

of landfilled trash and generates increased temperatures (Shi et al. 2021; Kumar et al. 2020). Organic wastes, on the other hand, decompose aerobically, transiently, and anaerobically in landfills. The maximum temperature output occurs during the beginning of anaerobic degradation; however, all three phases contribute to heat creation (Khire et al. 2020). The entry of oxygen into landfills initiates exothermic decomposition in landfills through a number of other actions, including suboptimal soil cover, rapid settlement, passive venting, and sewer systems, all of which enable the supply of oxygen to the waste. Several other mechanisms have been reported to produce landfill heat, such as hydration of ash (Hao et al. 2017; Jafari et al. 2014), along with metal corrosion (Calder and Stark 2010), pyrolysis (Benson 2017), and spontaneous combustion (Gray 2016). The highest temperatures at MSW dumps are typically not more than 55 °C, and the heat produced by biotic reactions is equilibrated by releasing it into the surroundings (Hanson et al. 2013, 2010).

Factors affecting heat generation in landfills

Landfills produce heat as a result of the biological breakdown of MSW. Most MSW dumps have average temperatures of ≤ 55 °C; however, a small percentage of landfills have seen extreme temperatures of ≥ 93 °C. At temperatures ≥ 93 °C, difficult conditions like excessive settlements, differential settlement, and heat softening have caused infrastructure damage to gas wells and leachate collection system pipe-work and variations in leachate and gas quality. The potential contributors to the development of elevated temperatures (ETs) are (i) daily oxygen influx into the landfills due to inadequate construction and operation of LFG wells (Martin et al. 2013), (ii) high moisture content of organic waste which promotes faster biological reactions (Tupsakhare et al. 2020), (iii) reduced convective cooling from infiltration as a result of restricted vertical infiltration through the waste (Yeşiller et al. 2016), (iv) induction of exothermic aerobic reactions due to slumping or slope failures causing oxygen entry in the landfills (Yeşiller et al. 2016), (v) pyrolysis and high temperature combustion (Jafari et al. 2017), (vi) heat production related to climate change in landfills, and (vii) long-term deactivation of gas wells in landfills (Joslyn 2019). Some of the important factors responsible for heat generation in landfills are the following:

Landfill depth

The bulk of waste placed near the cover is impacted by seasonal fluctuations in temperature, followed by an escalating lag phase with augmented depth (Xiao et al. 2022). Van Elk et al. (2014) discovered that waste temperature rose with depth in terms of temperature distribution. According to the observations of Zhang et al. (2022) and Reinhart et al. (2017), the highest temperature was recorded in the center of the landfill. However, Zhang et al. (2019a) reported a maximum temperature around the level of leachate in a freshly filled waste layer.

The age of waste

Numerous studies have found the influence of waste age on heat production (Khire et al. 2020; Hanson et al. 2005). With time, the temperature varies, and it has been observed that the temperature of the garbage increases rapidly during the early phases of landfilling (Nocko et al. 2019). Hanson et al. (2013) documented a higher heat production rate in MSW landfills in the initial stages that reduces as the waste ages in landfills. Similarly, Yoshida and Rowe (2003) reported that the temperature of the waste began to drop after around 10 years. According to Yeşiller et al. (2015), the placement of new waste piles on top of older stock usually results in an upward movement of the maximum temperature.

Table 1 Typical composition of municipal solid waste produced in different countries of the world

Country	Organic/food (%)	Paper/cardboard (%)	Plastic (%)	Textile (%)	Metals (%)	Glass (%)	Leather/rubber (%)	Wood (%)	Miscellaneous (%)	References
Ghana (Africa)	48.6	7.1	20	4.2	1.2	1.0	1. 5	0.3	5.3	Sarquah et al. (2023)
Ethiopia	68.40	1.50	1.90	0.96	0.30	0.30	0.50	-	6.90	Fereja and Chemeda (2022)
India	34.82	4.02	3.69	3.66	2.04	2.12	1.03	1.27	6.34	Nain et al. (2021)
Kazakhstan	46.3	12.8	15.2	-	1.9	4.9	-	0.8	1.0	Abylkhani et al. (2021)
Bangladesh	78.9	9.5	3.1	-	1.1	0.5	-	-	-	Ashik et al. (2017)
Tanzania	57.21	6.12	13.08		1.02	2.32				Kazuva and Zhang (2019)
Iraq	54.8	7	25.2	3.5	3.04	2.92	0.54	2.6	0.4	Abbas et al. (2016)
Malaysia	25.33	17.59	5.16	3.68	1.02	0.85	3.14	1.38	-	Yusoff et al. (2018)
Russia	28.6	5.94	-	-	-	13.29	-	-	-	Sereda (2021)
Jordon	53	9	12.85	10.22	4	-	-	-	-	Saidan et al. (2017)
Kazakhstan	47.6	6.2	12.5	3.4	2.0	6.2	-	-	-	Abylkhani et al. (2019)
Russia	38.72	31.03	26.96	33.04	16.79	31.47	17.05	8.16	-	Azarov et al. (2020)
India	29	4	25		2	1	-	-	-	Ali and Ahmad (2019)
Canada	65	26	8	-	35	-	-	-	-	Wang et al. (2016b)
Nigeria	24.1	9.8	10.2	13.2	6.4	9.3	-	-	-	Abubakar et al. (2018)
Saudi Arabia	48	20	25	1	4	2	-	1	-	Osra et al. (2021)

Waste placement conditions

The amount of heat in landfill waste is influenced by waste disposal conditions, and waste that is dumped slowly generates more heat over time (Yeşiller et al. 2005). The initial waste temperature and waste placement rates are among these conditions, and there is a substantial positive association between the original waste temperature and heat content. It was observed that waste landfilled during warmer seasons reached higher maximum temperatures than waste landfilled during cooler seasons (Kumar and Reddy 2021). Moreau et al. (2019) reported that waste temperature in the landfill grew dramatically throughout the period of waste disposal while being reduced when the landfill was closed.

Climatic conditions

Climate drastically contributes to landfill heat production (Chavan et al. 2022). The climatic conditions significantly influence the temperature and amount of heat in the landfills located in different regions (Yeşiller et al. 2005). Temperature variations in landfills are caused by seasonal climatic changes that alter microbial dynamics, cause bioprocess regression, and decrease waste decomposition efficiency. With increased precipitation, the heat content increases and reaches its maximum at a specific rate of precipitation. Even if the waste is not frozen at the time of placement, waste material landfilled during the warmest months of the year may attain higher maximum temperatures than waste material landfilled during the cooler months (Yeşiller et al. 2015). This also means that waste dumped in warmer climates achieves higher temperatures on average than waste dumped in cooler climates.

Role of indigenous microbes

The majority of bacteria that cause the degradation of landfill waste are mesophilic in nature (Fei et al. 2015), with the exception of methanogens, which are thermophilic (Hao et al. 2017). Similarly, in temperate climatic conditions, landfills harbor cold-active microbes, which actively participate in landfill waste decomposition at the upper cell surface. The microbial activities lead to increased temperatures and create thermal zones at the deeper and central landfill layers. Organic waste decomposition by microbes significantly contributes heat to elevated-temperature landfills (ETLFs) (Yeşiller et al. 2005). The breakdown of waste anaerobically is likewise not likely to produce extreme heat in ETLFs since methanogenesis discharges little exergonic heat in comparison to anaerobic metal corrosion and ash hydration and carbonation (Hao et al. 2017). The process of methanogenic decomposition is exothermic, leading to high temperatures inside the landfill (Grillo 2014).

Landfill leachate: generation and composition

The most common way of disposing MSW is landfilling. Leachate is the most toxic by-product of municipal waste decomposition (Abdel-Shafy et al. 2023). Generation of landfill leachate occurs as a result of rainfall percolation or groundwater infiltration into the landfill, which causes various biological and chemical reactions within the landfill (Podlasek et al. 2023; Wijekoonet al. 2022). Landfill leachate consists of various physicochemical contaminants, such as organic compounds, inorganic compounds, ammonia, xenobiotics, HMs, and biological organisms (Abdel-Shafy et al. 2023; Mojiri et al. 2016). The physicochemical characteristics of landfill leachate from different landfills are demonstrated in Table 2. The leachate quantification method becomes more challenging and complex when these elements change over time and space (Grugnaletti et al. 2016). The leachate constitution differs based on the type, composition, generation rate, and moisture of waste, as well as landfill age, hydrology, weather conditions, and landfill design parameters (Moustafa et al. 2023; Mojiri et al. 2021; Costa et al. 2019).

Landfills and ecotoxicological effects

The major concern regarding improper management of MSW and landfilling is the generation of gases, heat, and leachate that can lead to water pollution, fire explosions, global warming, air pollution, and other human health hazards. Some of the important ecotoxicological issues related to these are discussed in the following subsections:

Landfills and water pollution

Water pollution has been a worldwide issue, posing constant and significant danger to the surrounding nature and wellbeing of human beings (Bhowmick et al. 2018). Landfill leachate, containing a broad array of toxic and hazardous substances, has emerged as a key anthropogenic cause of water pollution (Dhamsaniya et al. 2023; Negi et al. 2020). Most landfills, particularly in underdeveloped nations, are built without designed liners and suitable leachate collecting systems (Alam et al. 2020), which lead to surface and groundwater pollution (Dhamsaniya et al. 2023; Mangimbulude et al. 2009). Once groundwater gets contaminated, pollutants persist, and it becomes challenging to remediate because of poor access, extended life, and huge volume (Wang et al. 2012). Mainly, groundwater pollution occurs within a 1-km radius of a landfill site, with

Table 2 Physicochemical characteristics of landfill leachate in different countries (mg/L)

Country	COD	BOD	NH4-N	pH	Fe	Pb	Ni	Cr	Cd	References
Iraq	-	-	-	7.29	-	12.41	22.33	19.70	5.00	Jalal and Darwesh (2023)
Colombia	23,688.00–34,405.00	2724.85–3684.43	-	7.94–8.92	-	-	-	-	-	Gutiérrez-Mosquera et al. (2022)
Poland	954.0–4270.0	-	17.6–231.2	7.8–9.1	1.6–18.0	0.0–0.2	0.0–0.1	0.0–0.5	0.0	Wdowczyk et al. (2022)
Morocco	21,817	10,192	3317	7.88	59.53	-	0.7725	7.976	0.0251	Zaki et al. (2022)
Malaysia	1633	137.41	400	8.25	8.457	0.110	-	0.453	-	Zaini et al. (2022)
Malaysia	2214	-	454	8.4	-	-	-	-	-	Shadi et al. (2021)
Poland	1900	64	-	7.8	5.611	0.000044	0.166	0.611	0.01	Jabłońska-Trypuć et al. (2021)
Bangladesh	1397–1511	157–182	-	7.87–8.07	14.4	0.01	0.01	0.056	-	Akter et al. (2021)
China	2078.22–7695.04	-	366.46–1444.38	8.2	-	-	-	-	-	Song et al. (2020)
Croatia	673–1653	108–288	-	8.09–8.63	< 0.05	< 0.025–0.34	0.10–0.231	< 0.010	< 0.010	Ančić et al. (2020)
Vietnam	3308–3540	823–1274	1006–1197	7.9–8.5	-	-	-	-	-	Luu (2020)
Iran	11,774	8634	-	7.73	41.80	0.213	3.465	0.176	-	Vahabianet al. (2019)
India	1800	368	182	7.84	45.8	-	9.9	1.4	-	Nair et al. (2019a)
Italy	629–1070	23–29	-	7.8–8.0	1.65–4.35	-	0.09–0.16	0.06–0.19	-	Fasani et al. (2019)
Algeria	-	-	-	7.0–7.5	-	7.3–60.4	20.0–42.2	76.0–98.9	0.5–1.6	Mouhoun-Chouaki et al. (2019)
China	2000–30,000	90–950	1.5–150	7.56–8.09	30–98	0–36	0.8–3.8	0.7–4.8	-	Ren et al. (2018)
China	6140	558	1856	-	-	0.31	-	0.052	0.01	Hu et al. (2016)

most of the stern pollution of the groundwater occurring within a 200-m radius (Han et al. 2016). Water pollution is far more common in regions around landfills, owing to the existence of leachate as a possible source of pollution.

In recent years, many leachate-based water pollution cases have been documented, particularly in poor nations. Mishra et al. (2019) investigated groundwater quality near Ramna landfill in Varanasi City (India) and found that the groundwater quality was steadily deteriorating owing to landfill leachate leaching. They further found that the water was unsafe to consume since the majority of the physicochemical characteristics exceeded the WHO and BIS permitted limits for drinking water standards. Nagarajan et al. (2012) also found greater amounts of chorine, nitrate, sulfate, and ammonia in groundwater samples near landfills, suggesting that leachate percolation is affecting groundwater quality. Ammonia-N is a key contaminant in leachate because it may stay in water bodies, posing a menace to humans and aquatic organisms (Yenigün and Demirel 2013). Several studies have found significant concentrations of ammonia-N in landfill sites (Jahan et al. 2016), which, if not handled appropriately, may cause major consequences on water quality (Parvin and Tareq 2021). Negi et al. (2020) also found greater levels of ammoniacal nitrogen in water samples taken at a low depth and distance from the landfill.

The occurrence of HMs is one of the gravest contaminants in leachate, which causes a serious risk to the wellbeing of humans (Parvin and Tareq 2021). In many parts of the globe, leachate samples taken from landfill sites are enriched in HMs, causing a rise in the concentration of HMs in groundwater (Alam et al. 2020; Hossain et al. 2018). Murtaza and Sabihakhurram (2018) reported that HM concentrations in groundwater such as Cd, Cu, As, and Pb were greater compared to the allowable limit. In a recent study conducted in Ghana, Amano et al. (2021) studied various physico-chemical parameters and concentrations of HMs in surface waters and underground water close to landfill site and reported that the HM pollution index (HPI) shows that the water sources were beyond the safe drinking water threshold. They further revealed that Cd concentrations in surface waters and underground water in the vicinity of the landfill site were much higher than the WHO standard, deeming them unfit for consumption. The literature findings also evidenced the enhanced levels of other HMs, for instance, Pb, Fe, Cr, and Cu, which may add to the risk of toxicity at landfill sites (Olagunju et al. 2020; Vongdala et al. 2019). Other pollutants, such as chloride, calcium, bromine, phosphate, and nitrate, have been found in high amounts in ground and surface water sources, perhaps owing to their closeness to landfill sites, rendering the water unsafe for human consumption (Amano et al. 2021; Negi et al. 2020).

Landfills and human health effects

Health effects by heavy metals and other pollutants

Landfill leachate is a major problem because of its intricate blend of contaminants, including HMs, dissoluble inorganic and organic chemicals, suspended particulates, and nutrients such as nitrates and phosphates (Beinabaj et al. 2023; Negi et al. 2020). Some of these contaminants, especially HMs, can make their way into the food chains and influence human health (Fig. 6) (Iravanian and Ravari 2020). The main HMs present in leachate are Cd, Cr, Hg, Cu, Zn, Pb, and As (Chu et al. 2019), and the potential contributors of these HMs are batteries, plastic, lead-based paints, and electronic wastes dumped into landfills (Boateng et al. 2019; Han et al. 2014). The primary routes of human exposure to hazardous metals have been identified as drinking water and inhaling soil particles (Zhu et al. 2011).

Underground water contaminated with leachate causes environmental concerns such as water blooms and soil salinization, in addition to inducing a variety of aquagenic ailments if consumed or bathed in. For example, long-term use of groundwater contaminated with heavy metals increases cancer risk and infant mortality and also causes motor and cognitive problems in kids (Parvez et al. 2011; Rahman et al. 2010). Other HMs, for instance, Cr, Cd, Hg, and Cr, are also effective toxins, and their high concentrations can cause respiratory issues, skin cancer, and damage liver, renal, neurological, and immunological systems (Mohammadi et al. 2020; Godwill et al. 2019). Nagarajan et al. (2012) observed elevated levels of other pollutants like chlorine, total dissolved solids, nitrate, and fluoride in groundwater near the Vendipalayam landfill. Phosphate and nitrate provide nutrition to microorganisms, but their high levels degrade the quality of drinking water and make it unsafe for consumption (Wang et al. 2018a, 2016a). Excess nitrogen in the blood causes methemoglobinemia-like conditions in cells by lowering hemoglobin's oxygen-binding ability (Sadeq et al. 2008). Furthermore, nitrate is common in MSW landfills, and this compound has been linked to unexpected miscarriage and an augmented danger of non-Hodgkin's lymphoma (Martínez et al. 2017; Gurdak and Qi 2012).

Health effects by pathogens

Contamination of groundwater with dangerous microbes as a result of leachate leakage poses a serious hazard to human health and has become a global environmental issue (Xiang et al. 2019). Various studies have revealed that *Escherichia coli* concentrations in landfill leachate are high (Umar et al. 2011) and contain pathogenic genes (Shi et al. 2018). As a result, numerous studies have revealed the degree of contamination of underground water with *E.*

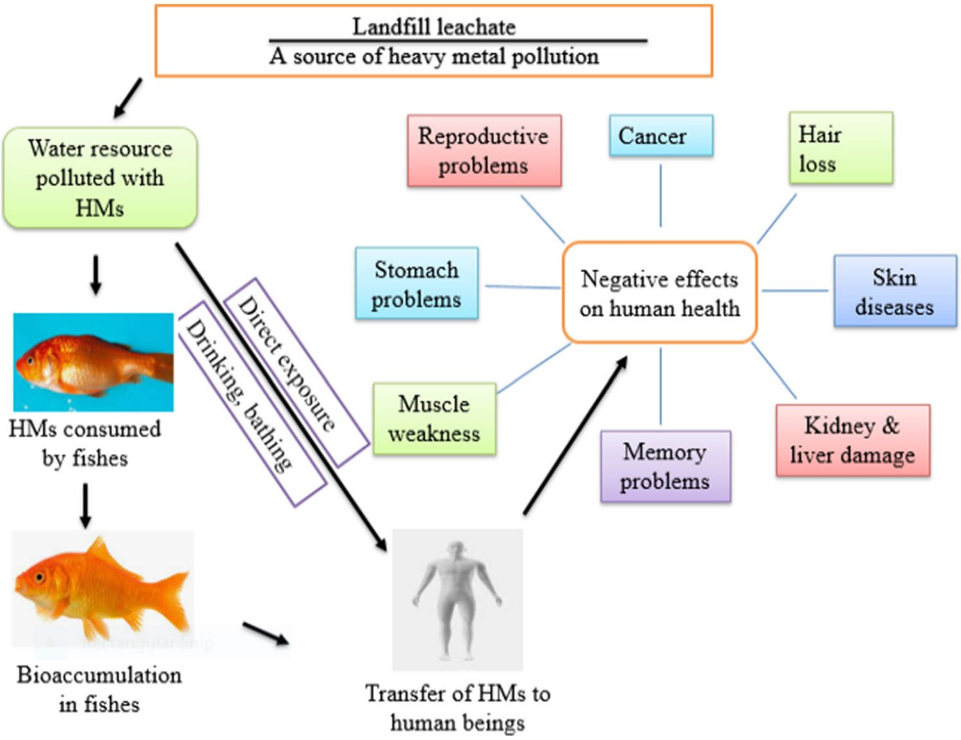


Fig. 6 Landfill leachate, an important source of heavy metals, leads to water pollution, which in turn causes various health hazards in human beings upon exposure

coli from leachate and unprocessed wastewater. Moreover, the presence of coliform bacteria in drinking water has been substantially linked with diarrhea (Aziz et al. 2013). Diarrhea has been linked to around 1.5 million infant fatalities annually, according to estimates (Fenwick 2006). Poor hygienic measures and drinking contaminated water are responsible for 90% of global diarrheal disease (UNICEF 2012).

Furthermore, microbially polluted groundwater is the source of many outbreaks of aquagenic diseases. Xiang et al. (2019) observed that different disorders of the human digestive tract occur due to pathogenic *E. coli* owing to the presence of particular genes of pathogenicity and factors of colonization and virulence. The leachate combined with the unrestricted aquifers generates plumes, which may stretch to hundreds of meters and influence the aquifer's hydrogeological system (Mor et al. 2016). Maiti et al. (2016) performed research at the Dhapa landfill site (Kolkata) to determine the influence of the leachate plume on health and reported many health-linked problems, including diarrhea, nausea, stomach discomfort, and other liver and intestine-related health issues, among the populace living close to the mentioned landfill site. Negi et al. (2020) recently conducted a microbiological examination of water samples and found that more than 40 and 52% of the samples were poor and unsafe for drinking during the pre- and post-monsoon periods, respectively. They also revealed that groundwater samples taken near the Mohali landfill (India) showed substantial organic pollution, owing to open defecation surrounding the wet land, open drains, and landfill leachate, which caused pathologic contamination to infiltrate into the subsoil.

Landfills and fire hazards

On a global scale, landfill fires are a major environmental hazard (Obeid et al. 2020; Morales et al. 2018) that are most common during the summer months (Milošević et al. 2021). Because of the harmful chemical substances they produce, landfill fires present the main menace to environmental and human wellbeing (Aderemi and Otitoloju 2012). In underdeveloped nations, where landfills are non-engineered and frequently located near residential areas, the risk of a landfill fire is relatively high (Chavan et al. 2019). In most cases, large amounts of municipal garbage containing a range of combustible compounds that are placed in landfills represent a considerable danger of fire. The existence of CH_4, which is emitted by waste decomposition, raises the risk level since methane is very combustible and explosive (Milošević et al. 2021). The biochemical activities occurring over-surface and within the landfill create a tremendous quantity of heat and gases (Chavan et al. 2019), and this buildup of heat causes fire hazards (Annepu 2012). The existence of SW, together with heat produced and O_2 influx, all contribute to the formation of ingredients required for fire initiation (Moqbel et al. 2010). The inadequate dissipation of the heat produced raises the ignition temperature of SW constituents beyond the threshold, which causes fires in landfills (Morales et al. 2018).

Landfill fires may endanger the surrounding area and public health by releasing hazardous chemicals into the air (Morales et al. 2018). It also has a larger influence on the landfill's structure (Morales et al. 2018). Landfill fire emissions, due to their highly chronic and hazardous nature, frequently cause all-encompassing ecological and health catastrophes for down-wind residents (Mazzucco et al. 2020). Several studies have found that waste fire emissions cause persistent health problems, for instance, lung cancer (Wiwanitkit 2016), gestational issues (Mazzucco et al. 2019), and abnormalities of the heart, lungs, and nervous system (Adetonaet al. 2020).

Landfills and atmospheric pollution

Nowadays, atmospheric pollution is a major issue in big cities, owing to the presence of significant levels of organic compounds in MW (Talaiekhozani et al. 2018). Landfill gases like CH_4, CO_2, and volatile organic compounds (VOCs) are released by the anaerobic breakdown of organic wastes in landfills (Mor and Ravindra 2023; Nair et al. 2019b). VOCs are a type of air pollutants that may be unsafe to both the environment and human wellbeing (Lakhouit and Alsulami 2020). Benzene, toluene, ethyl-benzene, and xylene isomers (also known as BTEX) are some of the typical VOCs observed in landfill biogas (Lakhouit and Alsulami 2020). VOCs are common pollutants that are emitted into the atmosphere from landfill sites as a result of the breakdown of organic stuff and recent domestic items such as cleaning agents, sterilizers, and personal care products that are found in dumped MW (Nair et al. 2019b). The high moisture and temperature provide an ideal environment for microbes to decompose the organic waste, thereby generating greater VOC quantities (Carriero et al. 2018). A significant quantity of VOCs is also emitted into the atmosphere during fires in landfills and the burning of waste.

In most metropolitan areas, the negative effects of VOCs emitted into the atmosphere from landfill sites are a serious issue (Nair et al. 2019b). The biogas generated from landfill sites increases the risk of contracting cancer in workers and communities that live near dump sites (Lakhouit and Alsulami 2020). VOCs produced from landfills can react photochemically with hydroxyl radicals and nitrogen oxides in the troposphere to produce ozone, secondary organic aerosols (SOA), and photochemical smog, all of which can harm both human fitness and the quality of the air (Nair et al. 2019b; Kumar et al. 2017). Ground-level O_3 adversely affects the health of people, plant development, and material longevity (Awang et al. 2016). SOA is made up of a large number of distinct fragments that are created from various precursors, and as a result, it may have a major impact on the area's visibility, air quality, and temperature (Ziemann and Atkinson 2012). SOA may deflect solar radiation and generate cloud condensation nuclei, causing the earth's overall radiation budget to be disrupted (Schneidemesser et al. 2015). Furthermore, many VOCs can trigger allergies and asthma, as well as have a deleterious impact on lung function (Cakmak et al. 2014; Kim et al. 2013). Some VOCs are thought to be carcinogenic to landfill workers and the people who live nearby (Majumdar and Srivastava 2012). Residents living near landfills, as well as landfill workers, are in danger of breathing VOCs, which can cause acute or chronic sickness (Lakhouit and Alsulami 2020). According to various studies, BTEX is a carcinogenic chemical renowned for its capacity to harm human health (Rafiee et al. 2019; Garg and Gupta 2019). Durmusoglu et al. (2010) conducted a cancer risk assessment for landfill workers in Italy based on BTEX emissions and found that 67.5 people per million are at risk of cancer, primarily owing to benzene exposure.

Landfills and global warming

Researchers in several countries have recently found that landfills are the most important cause of greenhouse gas (GHG) emissions (Ghosh et al. 2023; Zhang et al. 2019b). The principal GHGs emitted by landfill sites owing to the biodegradation of organic waste are CO_2, CH_4, and N_2O (Milovanovic et al. 2021; Gollapalli and Kota 2018). These GHGs emitted from municipal organic waste contribute to worldwide temperature rise and climatic changes (Tominac et al. 2020). Other possible sources of GHG emissions from the waste management system include waste collection trucks, landfill machinery, and landfill fires (Milovanovic et al. 2021). As per the report by Kaza et al. (2018), the management of waste contributes roughly 5% of global GHG emissions. Singh et al. (2017) reported that landfills produce one third of total anthropogenic CH_4, which is a significant contributor of GHGs to the atmosphere. CH_4 is one of the most significant GHGs due to its enormous potential for global temperature rise, which is 28 times higher than that of carbon dioxide (Du et al. 2017). Gupta et al. (2022) recently revealed that landfills account for about 11% of the methane emitted worldwide. Increased GHG production leads to higher ambient temperatures, which leads to more rainfall, the melting of glaciers, changes in the hydrological system, and ocean acidification (IPCC 2014).

Landfills and odor pollution

Landfills are a source of odorous and hazardous substances (Mor and Ravindra 2023; Wu et al. 2018). The odor pollution brought on by MSW is a societal issue (Wu et al. 2017) and is one of the most important reasons for a growing number of complaints by residents living near landfills (Tansel and Inanloo 2019; Liu et al. 2019). Landfill emissions may negatively affect people's standard of living and the environment around them (Naddeo et al. 2018). The released gases and odors are mostly caused by the biodegradation of organic waste (Abdul-Wahab et al. 2017). MSW generates a substantial quantity of odorants in the form of hydrocarbons, organic alcohols, sulfur compounds, NH_3, and other VOCs (Sonibare et al. 2019). Several authors have reported that sulfur compounds like H_2S, di-methyl disulfide, and ethyl sulfide are prominent odor sources in landfills (Yao et al. 2019; Liu et al. 2018). Despite the fact that these offensive gases make up $< 1\%$ of overall emissions (Lim et al. 2018), the related environmental risk and discomfort for nearby inhabitants are major problems in landfill operation and development (Njoku et al. 2019; Liu et al. 2015).

The components of malodorous gases are affected by different variables, including landfill age and size, as well as environmental conditions like temperature, relative humidity, and atmospheric conditions (Wang et al. 2019; Yun et al. 2018a). High summer temperatures enhance odor emissions owing to an increase in the anaerobic activity of the microbes. Wu et al. (2018) recently observed that odor pollution was severe in the summer but significantly reduced in the winter. Tansel and Inanloo (2019) also discovered that the odor release potential during the winter months was lowered due to reduced biodecomposition rates at colder temperatures. Wind speed and direction might also play a role in changing odor concentration (Liu et al. 2019).

People living near landfills, especially in the downwind areas, are irritated by the foul odors from the landfills, lowering their standard of living and overall health (Potdar et al. 2016; Che et al. 2013). Long-term exposure to unpleasant scents might result in undesirable responses ranging from psychological to physical problems such as uneasiness, nausea, headache, and respiratory problems (Wu et al. 2015a; Palmiotto et al. 2014). In most situations, it is one of the most prevalent reasons for people to criticize the existing landfill sites and has also evolved into one of the biggest obstacles to the development of new landfill sites (Cai et al. 2015).

Municipal solid waste management: global perspective

Waste management is a critical service that necessitates planning, administration, and collaboration at all levels of government and stakeholders. The typical MSW management service involves waste collection from houses and business establishments, hauling it to a collection point, and then transporting it to a facility for ultimate disposal or treatment (Idumah and Nwuzor 2019). Globally, approximately 33% of waste is dumped openly, 37% is disposed of in landfills, 19% undergoes material recovery through recycling and composting, and 11% is handled through incineration (Kaza et al. 2018) (Fig. 7). Waste management practices differ significantly depending on the income level. In low-income nations where landfills are not yet available, open dumping and burning are common (Ferronato and Torretta 2019). In low-income nations, approximately 93% of waste is burned or dumped on highways, open fields, or water bodies, and only 3% of waste is recycled, whereas only 2% of waste is thrown in high-income nations, and around 29% is recycled and another 22% is incinerated (World Bank 2022; Kaza et al. 2018) (Fig. 8). Waste management becomes more sustainable as countries grow economically, and the first move towards eco-friendly treatment of waste is the development and use of landfills (He et al. 2022).

Sustainable and integrated municipal solid waste management strategies

MSW management requires special attention in order to recover resources and reduce environmental impact. MSW is a heterogeneous resource with a huge potential for energy, nutrients, and material recovery; thus, different management techniques can be employed. The different treatment options (Fig. 9) available with different capacities for the safe handling and recycling of MSW are described below:

Physical and thermal treatment of municipal solid waste

Sanitary landfilling

Building safe landfills for waste that is non-reusable and non-recyclable is an essential aspect of the sustainable management of MW. Sanitary landfills are one of the most secure and extensively utilized ways of MW disposal (Hereher et al. 2020). In these modern landfills, MW is confined by a liner system. Liners and drainage layers provide complementary roles in preventing the uncontrolled release of pollutants into the environment (Azad et al. 2013; Bhuiyan and Molla 2013). The operating procedures implemented in sanitary landfills, including landfill lining and capping, waste segregation, leachate collection, and treatment, have been shown to decrease the release of pollutants into the environment. In comparison to open landfills, sanitary landfills are thought to be a more environmentally friendly way of disposing of final waste. The designs and capacities of sanitary landfills make it easy to dispose MSW with respect to pre-sorting, leachate treatment, and methane gas recovery (Weng and Chang 2001). The greenhouse gas emissions from sanitary landfills are considerably lower (8%) compared to open land filling (33%) of MSW (Sabour et al. 2020). However, various studies have reported that the leachate generated from sanitary landfills contains pollutants like

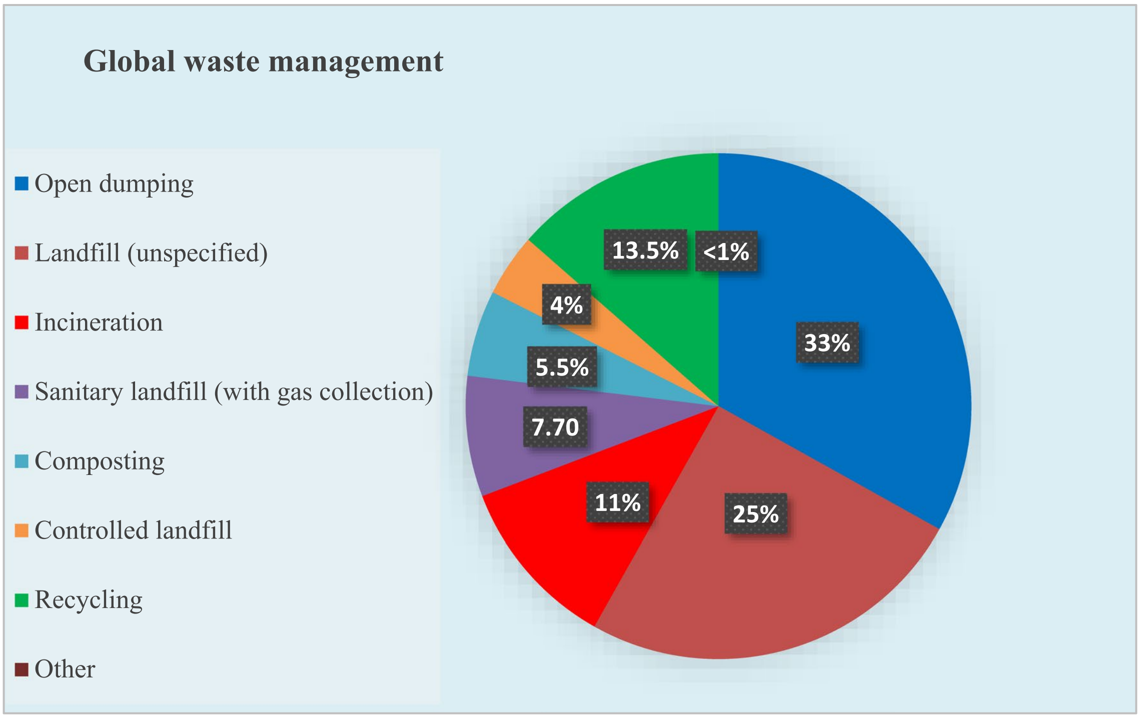
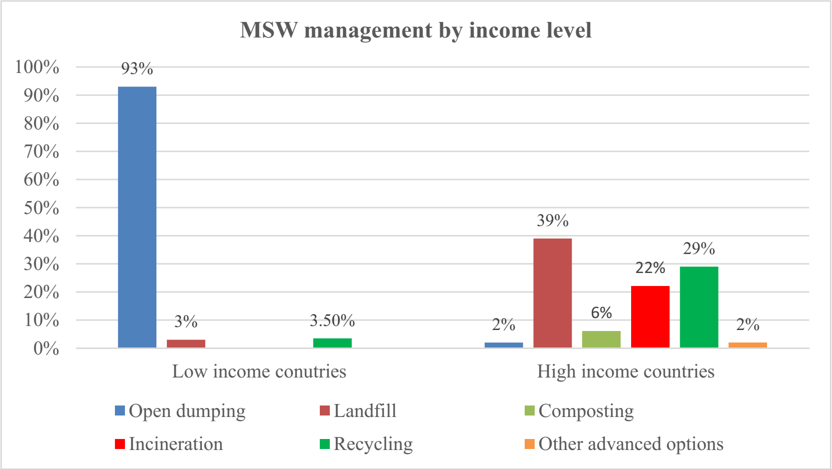


Fig. 7 Worldwide, around 33% of the waste is dumped openly, 13% is recycled, 11% is incinerated, and 37% is disposed of in some kind of landfill

Fig. 8 In low-income countries, around 93% of municipal solid waste is dumped openly and only 3% is landfilled, whereas in high-income countries, only 2% of the waste is dumped openly, 39% is landfilled, and 29% is recycled



HMs, endocrine disrupting substances, and other inorganic pollutants (Seibert et al. 2019; Adhikari and Khanal 2015). In addition, the locations of sanitary landfills are vulnerable to earthquakes, floods, and releases gases, HMs, and toxic leachates (Fernandes et al. 2015).

Pyrolysis

Pyrolysis is a viable and emerging MSW treatment technology (El Kourdi et al. 2023; Lu et al. 2020). It is a thermochemical process in which waste is broken down under anaerobic conditions at temperatures between 300 and 650 °C (Barry et al. 2019; Kalogo 2012). During the process, the products obtained from the conversion of organic ingredients include a gaseous product (syngas), a liquid (biooil), and a solid product (biochar) (Li and Skelly 2023; Ghodke et al. 2021). When compared to other thermochemical techniques, pyrolysis is a more eco-friendly alternative (Elkhalifa et al. 2019) and has attracted more interest owing to improved economic performance, increased efficacy, and a higher volume decrease (Mphahlele et al. 2021; Ambaye et al. 2021). The product

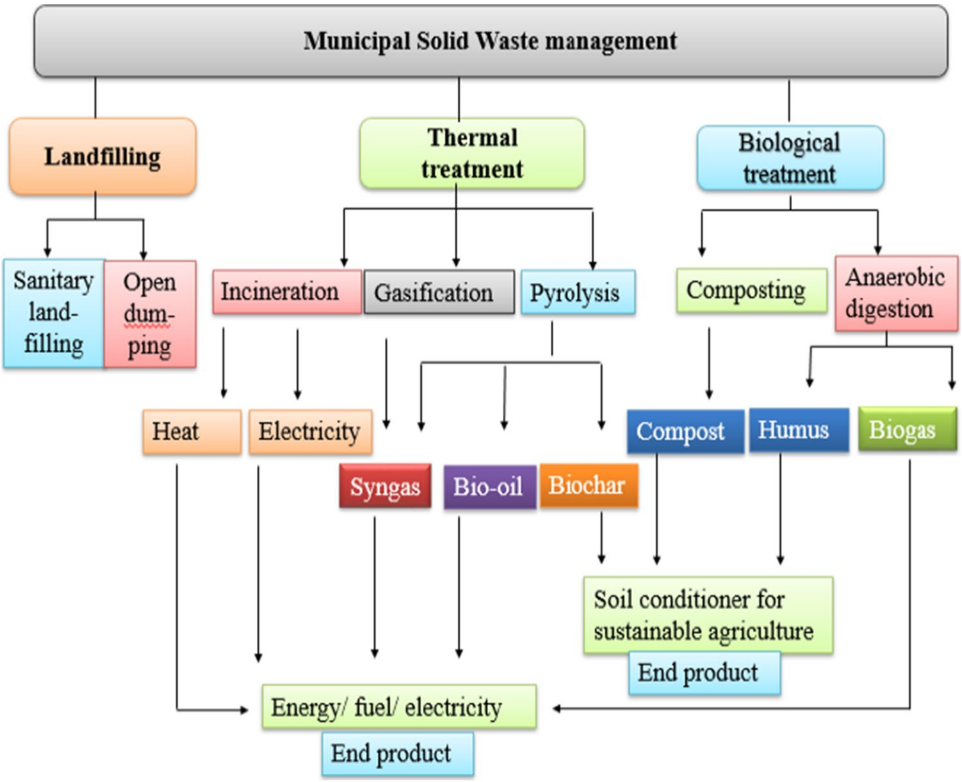


Fig. 9 Different integrated techniques for the sustainable management of municipal solid waste

quality and yield depend on waste composition, heating rate, residence duration, and pyrolysis temperature (Song et al. 2018; Lombardi et al. 2015). Djandja et al. (2020) reported that at elevated temperatures (over 600 °C), a substantial volume of syngas with higher proportions of carbon monoxide, hydrogen, methane, and carbon dioxide is produced from municipal sludge pyrolysis. Barry et al. (2019) revealed that when the pyrolysis temperature increases, the oil and gas yields also increase while the char yield decreases. The optimal temperature for rapid pyrolysis of MSWs is 510 °C with a maximum oil output of 67%, and part of this oil can be combusted back to meet the energy requirements of the pyrolysis procedure (Czajczyńska et al. 2017).

The key benefit of pyrolysis is that it is a low-cost technique that enables the reduction of environmental pollution, as both liquid oil and pyrolysis gases can be used as fuels based on their physicochemical characteristics (Ghodke et al. 2021), and biochar made from pyrolyzed waste can be used as organic manure in soils to improve water and nutrient retention (Elkhalifa et al. 2019; Ghodke et al. 2021). Furthermore, biochar can be treated further to produce other higher-value products like activated carbon (Elkhalifa et al. 2019). Thus, this technique of pyrolysis has received a lot of interest as a means to recover sustainable energy from biowastes because of its ability to transform waste into useful by-products (Gerasimov et al. 2019).

Incineration

Incineration is a valuable technique for managing the vast amount of MW and can be a potential alternative to landfilling, considering that landfilling MW is both costly and harmful (Alderete et al. 2021). It is a method of converting combustible fractions of waste into oxide forms like H_2O, CO_2, SO_x, and NO_x while recovering thermal energy (Havukainen et al. 2017). Incineration is capable of the overall destruction of a wide range of hazardous waste streams and is widely acknowledged as a technology for the direct recovery of energy and converting wastes into a stabilized form. It is one of the most frequent waste-treatment methods, reducing the weight and quantity of waste by 70 and 90 percent, respectively (Clavier et al. 2020; Lombardi et al. 2015); concurrently, it generates heat and electricity as well (Singh et al. 2011). Energy recovery during incineration is commonly used as a whole or as a partial replacement for fossil fuels in cement and power plants (Lu et al. 2017). However, by increasing the percentage of O_2 moles in the combustion air, oxy-combustion conditions are created, allowing for the recirculation of flue gas during incineration, resulting in a 3% gain in energy efficiency across the board (Vilardi and Verdone 2022). An important and reasonable argument for the promotion of incineration is that it is a preferable treatment to landfilling in densely populated areas. One of the primary benefits of the incineration of MSW is the eradication of all biological organisms and the mineralization of organic materials into safe by-products (Brunner and Rechberger 2015). For every tonne of MSW burned, a typical incinerator produces 544 kWh of energy and 180 kg of solid residue (Zaman 2010). In addition to volume reduction and power generation, incineration by-products (bottom and fly ash) can be utilized in constructing roads, manufacturing cement, and the production of other materials as they are rich in elements like silicon, aluminum, and calcium (Marieta et al. 2021). This offers the dual benefit of lowering landfill waste while also lowering the cement percentage in cementitious products (Alderete et al. 2021).

Thermal-plasma treatment

Plasma technology offers a viable alternative in MSW management. Plasma is the fourth important state of matter after solid, liquid, and gas and is mostly made up of ions, electrons, and neutral particles (Lane et al. 2020). For the management of SWs, plasma is considered the most feasible solution because of its capacity to provide a high temperature. Thermal plasma treatment is believed to be the most feasible solution to the escalating waste management crisis (Lombardi et al. 2015). Thermal plasma generates high temperatures, leading to high energy densities by plasma to treat MSW using the huge throughput generated in a small-scale reactor (Ruj and Ghosh 2014). The high energy flux densities at the boundaries of reactors rely on plasma as an energy source rather than conventional combustion fuels; as a result, little volume of gas is produced, making the process inexpensive and environment friendly (Li et al. 2016; Psaltis and Komilis 2019). Thermal plasma for waste treatment works either through plasma pyrolysis or plasma gasification. Pyrolysis through plasma gasification has the potential to transform MSWs into a valuable input in the circular economy, and its commercialization can be achieved by the value of gas or fuel from MSW (Munir et al. 2019). The treatment efficiency of plasma treatment is very high, with a reduction of 95% in the input of MSW.

Biological treatment of municipal solid waste

Composting

Composting is a technique that turns complex organic materials into a stable product (Awasthi et al. 2020). It is a low-cost and eco-friendly technology to deflect organic waste from landfills (Agapios et al. 2020). Composting can be done at any scale, from small-scale backyard composting to large MW treatment plants (Sayara et al. 2020). While composting is among the green alternatives for MW treatment (Lin et al. 2018), it has some drawbacks that have limited its use and efficacy. The drawbacks include low nutrient levels, odor pollution, nitrogen loss, pathogen detection, and GHG emissions (Ayilara et al. 2020; Soudejani et al. 2019). To overcome these shortcomings and produce a high-quality end product, critical parameters like pH, temperature, C/N ratio, and moisture must be maintained (Sánchez 2006; Tiquia et al. 2002). The rate of the entire process and the quality of the end product can also be improved by the inclusion of microbial inoculants, which directly affect the breakdown of biowastes (Onwosi et al. 2017). Several studies at waste management facilities and landfills have revealed that around 50–70% of MW is organic and may be recycled as compost (Kanat and Ergüven 2020; Chatterjee et al. 2013), thereby reducing the amount of pollution caused by inappropriate waste management significantly. Composting also produces less GHGs and leachate as compared to landfilling or open dumping (Kibler et al. 2018). Other advantages of composting comprise value-added product generation and a reduction in environmental pollution (Wang et al. 2018b). Furthermore, the use of compost in agriculture can help to maintain long-term soil productivity (Kamyab et al. 2015). Compost also has wide applications in bioremediation (Ventorino et al. 2019), weed suppression (Coelho et al. 2019), crop disease management (Sayara et al. 2020), enhancement of soil biota, and reduction of the environmental effects connected with inorganic fertilizers (Chelinho et al. 2019). Moreover, composting is a critical component of the circular economy since it helps to close the waste management cycle (Vaverková et al. 2020).

Anaerobic digestion

Anaerobic digestion (AD) has attracted increased scientific attention and is a promising treatment option for the management of MSW (Wang et al. 2023; Fan et al. 2018). AD is a regulated microbial decomposition process in which a microbial consortium converts organic refuse from MSW into CH_4, CO_2, inorganic nutrients, and humus (Macias-Corral et al. 2008). Some of the world's most technologically and agriculturally advanced countries have demonstrated AD as a viable option for waste management (Mu et al. 2018). The biodegradable part of MSW is pre-treated by sorting, separation, and sterilization, which is considered an important move in the yield output (Li et al. 2017). Recently, separation of the organic fraction of MSW through extrusion treatment appears to be an emerging technology to separate the organic fraction by using a high-pressure machine equipped with gates to spate the organic fraction effectively (Novarino and Zanetti 2012). AD not only recovers energy from MSW but also produces nutrient-rich soil amendment by reducing GHG emissions (Rogelj et al. 2016). The digestion efficacy of AD depends on the mode of operation. Thermophilic digestion is found to be suitable with biogas production between 13.92 and 83.25% (Mu et al. 2018) and is energy efficient if conducted in a thermophilic condition rather than a mesophilic condition (Wu et al. 2015b).

Management of landfill leachate

Landfill leachates from MSWs are the most significant source of environmental pollution (Teng and Chen 2023) because they percolate through soil and reach the surface and groundwater (Popovych et al. 2020). Long-term risk assessment of different sanitary landfills to the surrounding hydrological ecosystem is an extremely difficult task. To reduce the environmental impact of landfill leachates, a variety of cost-effective solutions have been investigated over time suitable for a variety of contaminants (Fig. S1). In the realm of landfill leachate treatment, a single method may not be able to meet all the requirements until new materials and combinations of technologies are involved based on feasibility (Bandala et al. 2021). The following sections provide critically recent insights into the physico-chemical and biological techniques utilized to remediate the pollutants contained in landfill leachates:

Physico-chemical treatment of landfill leachates

Coagulation-flocculation

Coagulation and flocculation methods are effectively utilized for removing suspended particulates from wastewater. The process works by destabilizing suspended particles with a negative charge into large flocs (Cheng et al. 2021). Nowadays, electro-coagulation (EC) and electro-oxidation (EO) have been considered versatile processes for landfill leachate treatment (Bahrodin et al. 2021; Ghanbari et al. 2020). Integration of EC and EO is a novel approach used for the successful removal of 60% organic loads and 80% discoloration in leachates, followed by degradation of organic compounds and successful abatement of 50% ammonium to minimize the organic load (Bandala et al. 2021; Adesida 2020). Although the EC-EO process is pH-independent (natural-alkaline pH), consequently, pH cost adjustment might be lessened for commercial applications; however, it is highly composition-dependent (Babaei et al. 2021). The pollutant elimination efficacy is determined by the current density of the electrodes and the catalytic load in the leachates. Pt and PbO_2 electrodes for the EC process and Al and Fe electrodes for the EO process are highly effective electrodes with COD removal efficiencies of 60% and 50%, respectively, at a current dosage of 50 mA/cm^2 (Ghanbari et al. 2020).

Adsorption treatments

Adsorption is an extensively employed treatment to eradicate ionic and molecular toxins suspended or dissolved in landfill leachates through interaction between electrically and chemically active surface-charged functional groups (Hedayati et al. 2021). Adsorbents' surface characteristics have a key role in determining the choice of adsorbent (Kaveeshwar et al. 2018). The most extensively used adsorbent for the treatment of landfill leachates is activated carbon, both in powdered and granulated form (Deng et al. 2018). Recently, various other substances, such as zeolites, clay, and magnetic adsorbents, have been reported as potentially effective for landfill leachate treatment compared to anaerobic composting (Augusto et al. 2019). Zeolites are made up of hydrated aluminosilicate crystals with a physical configuration comprised water-filled pores (Montalvo et al. 2020). The physical structure of zeolite, comprised cations (Ca^{2+}, K^+, and Mg^{2+}), is easily transferable by NH_4^+, and this capability of zeolites is one of its most versatile characteristics, with demands for future investigation (Aziz et al. 2020). Previous research demonstrated that a 10-g raw zeolite dosage can reduce NH_3-N, color, and COD by up to 53.1%, 46.0%, and 22.5%, respectively (Aziz et al. 2020). This indicates that a small quantity of zeolite can achieve optimal removal of toxins at a lower cost, making it suitable for leachate treatment on a broader scale. Clay minerals are regarded as superadsorbents and play an important role as pollutant purifiers because of their desirable features such as mechanical and chemical stability, high specific surface area, laminar structure, and high ionic exchange capacity. Bentonite clay (modified by L-glutamine) with a surface area of 28.98 $m^2\ g^{-1}$ reduces both COD and pH turbidity in leachates, which is attributed to more adsorption sites (Akl et al. 2013). The exterior surface of bentonite clay has weaker siloxane groups (Si–O), which later get transformed to Si–O bands and to Si–OH with a rise in pH to alkalinity, leading to a reduction in COD through precipitation (Hajjizadeh et al. 2020).

Advanced oxidation processes

Recently, a few advanced oxidation processes (AOPs) have been developed to efficiently treat landfill leachates. Photo-Fenton, electro-Fenton, and Fenton are successful AOPs and have been effectively used to treat landfill leachates by removing refractory organics (Gautam et al. 2019). The catalytic activity of Fe_2SO_4 during the Fenton reaction adds H_2O_2 to landfill leachates (Hilles et al. 2015). This technology, because of its eco-environmental advantages, has extensively been encouraged for landfill leachate treatment. Another effective and promising AOP generates in-situ coagulants and makes complex organic pollutants into simpler and nobler compounds like CO_2 and H_2O (Bashir et al. 2013). It is considered one of the greener technologies for the treatment of landfill leachates, and with further optimization, it may cause a COD reduction of up to 60% with a significant decline of metallic substances from 70 to 90% (Dhorabe et al. 2020). Sruthi et al. (2018) found that electro-Fenton produces the highest mineralization rate during 8 h of electrolysis, with a 96% removal of dissolved organic carbon from landfill leachates. The Fenton and ultrasonic flow cell method of AOP has a maximum synergetic effect and biodegradability index and has been recognized as a viable method of leachate treatment (Joshi and Gogate 2019). AOPs offer several benefits for the prevention and remediation of landfill leachates, including treating large volumes, automation, high energy efficiency, amicability, and easy and safe handling (Ribeiro et al. 2015). However, a few main drawbacks of AOP technologies are associated with costs involved in electricity, low conductance, fouling that causes loss of electrode lifetime, and loss of activity by high sludge formation (Sirés et al. 2014).

Biological treatment

Phyto-remediation of heavy metals from leachate

Phyto-remediation is a natural biochemical process in which plants use their root systems and rhizosphere microbes to mineralize, degrade, decrease, stabilize, and volatilize contaminants (Wibowo et al. 2023; Kristanti et al. 2023). It is an ecologically sound technique with long-term use for the elimination of contaminants (Ali et al. 2020). Some plant species frequently utilized for phyto-remediation have reduced many kinds of leachate pollutants. For example, water hyacinth has removed 24–80 percent of total HMs, including Cd, Cr, Cu, and Pb (El-Gendy 2008). Abbas et al. (2019) explored the potential of *Eichhornia crassipes* and *Pistia stratiotes* for landfill remediation and revealed the highest HM removal rates for Zn (80 to 90 percent), Pb (76 to 84 percent), and Fe (83 to 87 percent). They also observed that both plants considerably lower the other physicochemical characteristics found in landfill leachate, such as pH, TDS, COD, and BOD. Plants in the leachate deplete dissolved CO_2 during the photosynthetic phase, favoring aerobic microbes to decrease BOD and COD (Mahmood et al. 2005). Mokhtar et al. (2011) also reported a 97% decline in copper via a phyto-remediation study employing *E. crassipes*. Jerez Ch and Romero (2016) assessed the viability of *Cajanus cajan* to eliminate Cr and Pb from landfill leachates and found the removal of Cr and Pb by 49% and 36%, respectively. They also reported nitrogen removal from landfill leachate, which resulted in the eradication of ammonia and mixed nitrite/nitrate species by 85% and 70%, respectively.

The plant system is a viable mechanism to remove organic and inorganic pollutants using diverse mechanistic approaches, including phyto-degradation, phyto-volatilization, phyto-extraction, phyto-stabilization, and rhizo-filtration (Fig. 10). Recently, Moktar and Tajuddin (2019) revealed that over a 30-day experimental period, cogon grass was able to extract HMs, including Pb, Cd, and Zn, from landfill leachate. Plants take up most of these HMs and other nutrients because they are necessary for enzyme activation for photosynthesis and plant growth (Chibuike and Obiora 2014). As a result, it is

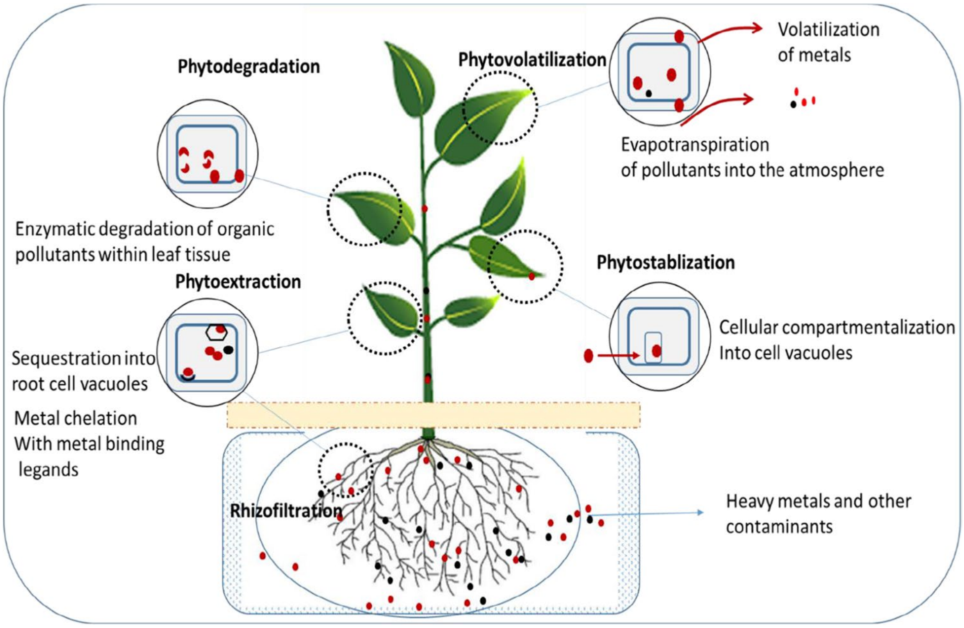


Fig. 10 Bioaccumulation of heavy metals and other pollutants from contaminated sites by plants through different mechanisms

strongly advised that the use of plants in the vicinity of leachate collection ponds be promoted in order to avoid the seeping of HMs and other leachate toxins into aquifers, which can pollute water bodies during overflow or discharge (Moktar and Tajuddin 2019; Ugya and Priatamby 2016).

Nano-remediation of landfill leachate

Nano-filtration (NF) is a membrane technology first used in the 1980s and is commonly applied for treating wastewaters (Reis et al. 2020) with characteristics that appear between ultrafiltration and reverse osmosis (Shahmansouri and Bellona 2015). Due to low energy requirements and greater flux rates, NF has largely been employed in place of reverse osmosis in numerous applications (Shon et al. 2013). The majority of NF membranes are fine film composites composed of synthetic polymers with functional groups, allowing them to effectively separate charged ions from wastewater (Siddique et al. 2020). The NF process efficiently separates the multivalent metal ions through sieving size and Donnan exclusion, which makes it a highly suitable low-cost separation technology (Pal 2015). The mechanism of filtration is based on screening and charge action in wastewater (Agboola et al. 2015). The NF device controls the filtration process through the NF membrane by regulating the backward surge of concentrated water. With an initial inlet waste water flow of 5 m^3/h, backward water flow of 4.5 m^3/h, and a membrane flux of 10 L/m^2/h, with a transmembrane pressure of 0.222 MPa, it could yield a water output of 7500–8500 gallons per day (Wang et al. 2020). The elimination rates of overall alkalinity, entire hardiness, and total soluble solids were 86%, 98%, and 91%, with a desalinization efficiency of 95% (Wang et al. 2020). Regular cleaning of NF membranes may well prolong their filtrating efficacy and serviceability. Deionized water containing HCl and NaOH, each with a concentration of 1 mol/L, can be used to clean and eliminate toxins from the NF membranes (Gao et al. 2011). Recently, carbon-based nano-treatments and nano-vermiculite mineral (NMV) have exhibited great adsorption capacity for the exclusion of numerous organic pollutants from landfill leachates owing to their extraordinarily precise surface area, excellent electric chemistry, and sorption sites (Duan et al. 2020). NMV is a novel material recently developed with excellent absorption capacity for ammonium from landfill leachates. In pilot-scale experiments, the size of the NVM particle (0.075–0.125 mm) used on ammonium-contaminated leachates decreased the ammonium concentration by 88% relative to the initial concentration (Rama et al. 2019).

Limitations and future perspectives

Municipal solid waste management (MSWM) is a complex and multidimensional challenge that involves technical, environmental, social, economic, and institutional aspects. MSWM aims to reduce the negative impacts of waste generation and disposal on human health and the environment while maximizing the recovery of valuable resources (Pal and Bhatia 2022). However, MSWM faces several limitations and future perspectives that need to be addressed. Some of these are the following:

- The lack of adequate data and information on waste generation, composition, collection, treatment, and disposal, which hinders the planning, monitoring, and evaluation of MSWM systems (Cayumil et al. 2021).
- The low level of public awareness and participation in waste reduction, reuse, and recycling, which limits the potential of waste prevention and resource recovery (Sewak et al. 2021; Almulhim and Abubakar 2021).
- The insufficient financial resources and institutional capacity to implement and sustain effective MSWM systems, especially in developing countries and low-income areas (Ferronato et al. 2020; Schübeler et al. 1996).
- The rapid urbanization and population growth, which increase the pressure on existing MSWM infrastructure and services, and pose new challenges for waste management in peri-urban and rural areas.
- The emergence of new types of waste, such as electronic waste, medical waste, and hazardous waste, which require specific management practices and technologies to ensure their safe handling and disposal (Shahabuddin et al. 2023; Andeobu 2023).
- Lack of adequate infrastructure, equipment, and facilities for waste collection, transportation, treatment, and disposal (Nepal et al. 2023).
- Limited integration and coordination among different stakeholders and sectors involved in waste management (Song et al. 2021).
- The high variability and uncertainty of the composition and characteristics of MSW and landfill leachate, which makes it difficult to apply standardized or universal solutions for their management and treatment (Lindamulla et al. 2022).

To overcome these limitations and explore future perspectives, MSWM requires a holistic and integrated approach that considers the entire life cycle of waste, from generation to final disposal. Such an approach should involve the following:

- Developing and implementing integrated and holistic waste management plans and strategies that consider the local context, needs, and priorities (Batista et al. 2021).
- Mobilizing adequate financial resources and creating economic incentives for waste prevention, reduction, reuse, recycling, and recovery.
- Promoting public awareness and education on the benefits of waste management and the responsibilities of waste generators and handlers (Debrah et al. 2021).
- Improving the data collection, monitoring, and reporting systems for waste management using modern technologies such as geographic information systems (GIS), remote sensing, and smart sensors (Singh et al. 2023; Fang et al. 2023).
- Fostering the collaboration and cooperation among different stakeholders and sectors involved in waste management, such as government agencies, private sector, civil society, academia, and international organizations (Vasconcelos et al. 2022).
- The adoption of the waste hierarchy principle, which prioritizes waste prevention, minimization, reuse, and recycling over energy recovery and disposal.
- The implementation of the circular economy concept, which aims to close the loop of material flows and reduce the dependence on virgin resources.
- The development of innovative technologies and practices, which enhance the efficiency and effectiveness of MSWM systems, such as smart waste collection systems, biodegradable packaging materials, waste-to-energy plants, and landfill gas recovery systems (Olalo et al. 2022; Kurniawan et al. 2022).

By addressing these limitations and future perspectives related to MSWM, it is possible to achieve a sustainable development goal that ensures a clean and healthy environment for all.

Conclusion

MSW is a global problem. Inappropriate waste collection and its management system contribute to major urban pollution with long-standing ecological impacts and effects on the wellbeing of humans, especially the poor. Traditional techniques, including burning, landfilling, and unscientific dumping of waste, cause various ecological concerns, including water contamination, global warming, and other effects on human wellbeing. Thus, to achieve sustainable development, MSW needs to be dealt with proper planning and execution. This can be accomplished by implementing integrated waste management policies that cover all aspects of waste generation, segregation, transport, treatment, resource recovery, and safe disposal through an engineered landfill, as well as emphasizing effective resource allocation. In addition, waste-to-energy technologies, for instance, incineration, anaerobic digestion, gasification, and pyrolysis, have steadily gained recognition across the world as crucial aspects of MWM. This review suggested that if waste-to-energy advanced techniques are adopted, MSW might be a key promising renewable energy source, not only reducing reliance on traditional fuels to meet the ever-mounting need for energy but also managing the waste management issue. Taken together, the review concluded that integrated waste management, together with energy and material recovery, could be the best alternative for the sustainable management of MSW, assisting in minimizing the negative consequences associated with MSW and fulfilling the aims of achieving sustainable development.

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